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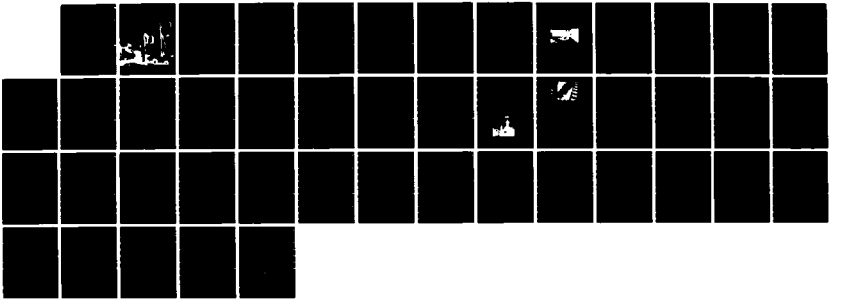

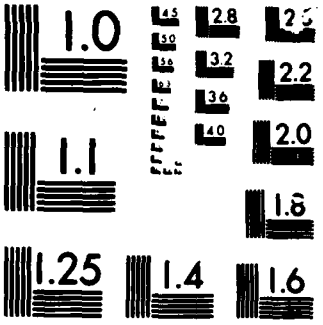

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Nitrogen removal in cold regions trickling filter systems

S.C. Reed, C.J. Diener and P. Butler Weyrick

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Trickling filters are found in about 50% of the operating wastewater treatment systems owned by the U.S. Army, and more are likely for any new construction. Control of nitrogen, particularly ammonia in wastewater effluents, is a growing necessity. Ammonia can be removed in trickling filters but the process is temperature-dependent. This study combined an intensive literature review with data collection at full-scale and pilot-scale systems. These results are presented and evaluated. A liquid temperature of at least 7°C is necessary in the filter bed for effective ammonia removal, and a separate single-purpose filter bed dedicated for nitrification is recommended when significant ammonia removal

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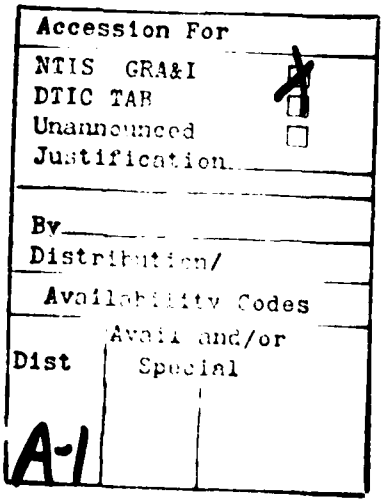
is required at cold regions locations. Criteria and equations are derived for future cold region system designs.

PREFACE

This report was prepared by Sherwood Reed, Environmental Engineer, Carl Diener, Civil Engineering Technician, and Patricia Butler Weyrick, Physical Science Technician, of the Civil Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this effort was provided by DA Project 4A762730AT42, Design, Construction and Operations Technology in Cold Regions; Task C, Cold Regions Base Support, Maintenance and Operations; Work Unit 009, Water Supply and Wastewater Treatment at Cold Regions Facilities.

The authors particularly thank Joseph Falcheck, William Rinaldi and William Kelly at the Tobyhanna Army Depot for their support and assistance in collecting field data at that site. The authors also gratefully acknowledge the computational assistance of Barbara Meir, the meteorological assistance from Roy Bates, and the participation of John Bouzoun in the early stages of the CRREL pilot tests.

This report was technically reviewed by James F. Wheeler, U.S. Office of Municipal Pollution Control, Washington, D.C., and Barry H. Reid, U.S. Environmental Protection Agency (EPA) Corvallis Environmental Research Laboratory, Corvallis, Oregon.



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NITROGEN REMOVAL IN COLD REGIONS TRICKLING FILTER SYSTEMS

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INTRODUCTION

Trickling filters can provide a reliable, easy-to-operate and low cost method for wastewater treatment. Variations of the trickling filter process have been in operation since the 1890's. Until recently, a typical unit would consist of a partly buried tank, with underdrains, containing several meters of crushed stone or similar media; wastewater would be applied at the top by fixed or rotating sprinklers. The trickling filter concept is particularly well suited for small to moderate sized communities and military bases. Over half the wastewater treatment plants operated by the U.S. Army are trickling filter systems (Poon et al. 1984).

The term "filter" is a misnomer because most pollutant removal occurs via adsorption rather than filtration. A gelatinous film of microorganisms forms over the wetted surface of the media. This film adsorbs dissolved and colloidal-size particles from the wastewater. The media bed is actually designed as a counter-current unit, with wastewater flowing downward in thin sheet over the media and air flowing upward in the large pore spaces. Under normal operating conditions the bed is never saturated, and so the unit is considered to be an aerobic treatment process. However, the biological films will tend to be aerobic on their surfaces and anaerobic at the contact zone with the media (depending on the amount of oxygen diffusion through the film, and the thickness of the film). As the biological film ages, it thickens and eventually portions will slough off and pass through the pore spaces in the media. Separation of these solids typically occurs in a settling tank and some or all of the clarified effluent may be recycled onto the filter bed, depending on the particular operational mode. Since treatment depends on the biological films, a trickling filter can also be described as an "attached growth process." Recent variations of the attached growth concept include stacks of redwood slats and large plastic disks on a central shaft. The plastic disks (the media) rotate

Table 1. Characteristics of plastic and rock media (after Poon et al. 1984).

Characteristic	Media type	
	Plastic	Rock
Specific surface area	84-341 m^2/m^3	62 m^2/m^3
Void ratio	95%	46%
Weight	44-112 kg/m^3	1400 kg/m^3

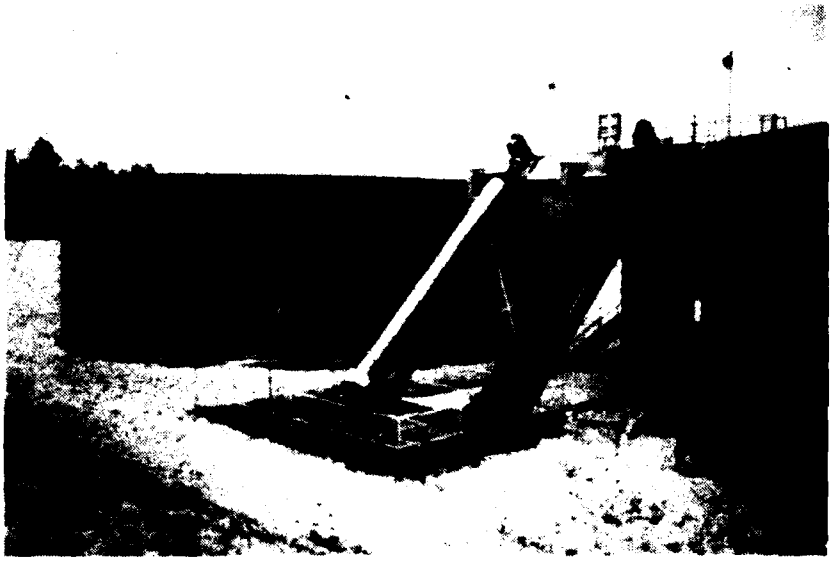

Figure 1. Plastic media trickling filter units at Tobyhanna Army Depot, Pennsylvania.

through the wastewater stream with the upper part of the disk exposed to the atmosphere during each rotation. These rotating biological contactors (RBC) appear to be a totally different system than trickling filters but the biological response is essentially the same.

Plastic has been used since the early 1950's to replace the rock media in trickling filters. Two basic types have evolved, both made from a variety of plastic. One is a modular, self-supporting unit fabricated from plastic sheets in a variety of configurations with overall dimensions of about 0.6 x 0.6 x 1.2 m. The second type consists of small plastic rings, 20 cm in diameter or less. The modular units are stacked in the bed area

while the rings are dumped in a random fill. Table 1 compares the characteristics of the plastic media to rock fill. The main advantages of the plastic are lower weight, much larger surface area and larger void ratio. These characteristics allow for significantly higher hydraulic loadings and much less expense for structural supports and container walls. Most conventional rock filters range from 1 to 2 m in depth. It is not uncommon to see plastic media in aboveground towers, 4 to 6 m tall, because of the improved conditions for both attached growth and natural airflow, and the low cost for the container. Figure 1 is a typical plastic media trickling filter unit.

Nitrogen in wastewater has been of increasing concern since the late 1950's. In a few special cases it may be necessary to remove most if not all of the nitrogen to protect drinking water sources and very sensitive receiving waters. In a great many cases it is only the presence of ammonia nitrogen that is critical. Ammonia nitrogen is toxic to a wide variety of fish (Ruffler et al. 1981) at very low concentration. In addition, the natural oxidation of ammonia in the stream will reduce the oxygen content of the water. As a result, many states limit the discharge of ammonia nitrogen. Treatment systems, including trickling filters, that discharge to such waters will require the removal or conversion (to nitrate, etc.) of the ammonia nitrogen in the wastewater, or both.

The initial purpose of this study was to evaluate the performance and the suitability of design criteria for ammonia nitrogen removal in trickling filter systems, with particular concern for cold weather and wintertime performance. The study was conceived as essentially a literature review with laboratory and field tests only undertaken if required by gaps in available information. Soon after the study commenced, we were told that the plastic media trickling filter system that was recently constructed at the U.S. Army Depot at Tobyhanna, Pennsylvania, was not satisfying discharge limitations for ammonia nitrogen during the cold weather period (November-March). We were asked to advise on remedial measures, and it was quickly obvious that a solution could not be obtained by recourse to the literature alone. As a result, our research involved measurements on the full-scale system at Tobyhanna and experiments with pilot-scale units at CRREL in Hanover, N.H. The purpose was to assist in the resolution of the specific problem at Tobyhanna as well as attempting to advance the state of the art on the general topic.

THEORY

Nitrogen in typical municipal wastewater ranges from about 15 to over 50 mg/L. About 40% is in the organic form, tied up in the protein molecules of animal tissue and fecal matter. The remaining 60% is in the ammonia form, either as ammonium ions (NH_4^+) or molecular ammonia (NH_3). The pH of the solution controls the equilibrium of these two forms so that at pH 7 essentially only ammonium ions are present, and at pH 12 only dissolved ammonia gas.

Oxidation reactions can convert organic N to ammonia, ammonia to nitrite and then nitrite to nitrate. The last two steps are controlled by the presence of specific bacteria:

Ammonia to nitrite:

$$2NH_3 + 3O_2 + \underline{\text{Nitrosomonas}} \rightarrow 2NO_2^- + 2H_2^+ + 2H_2O$$

Nitrite to nitrate:

$$2NO_2^- + O_2 + \underline{\text{Nitrobacters}} \rightarrow 2NO_3^- .$$

Both species of bacteria are typically present in the same matrix and the second reaction is quite rapid. As a result, negligible concentrations of nitrite are found in the effluent from most wastewater treatment processes.

Nitrate can be reduced to nitrogen gas (i.e. denitrification) by another species of bacteria. This requires an anaerobic environment and the presence of sufficient organic carbon to support the reactions. The inner contact surfaces of the biological films may be anaerobic in a trickling filter, but not enough organic carbon is typically available at that point in the film. Since the remaining portions of the system are aerobic, nitrogen removal via denitrification is not a significant factor in typical trickling filters.

The nitrifying organisms are controlled by pH, water temperature, alkalinity and dissolved oxygen. A pH of 8.4 is optimium but the species can acclimate to a pH in the range of 6.6 to 9.0 without significant decrease in performance (Ericsson 1975). Liquid temperatures below 4°C essentially halt the activity, but reaction rates then increase throughout the range of 4°-35°C. Dissolved oxygen concentrations below 0.5 mg/L inhibit reactions, but this should not be a factor in the surface films in a typical trickling filter. Alkalinity of the liquid is important since 7.14 mg of alkalinity (as $CaCO_3$) is consumed for each milligram of ammonia

nitrogen that is oxidized. If sufficient natural alkalinity is not present, the addition of lime, or other bases, should be considered.

Wastewater composition is also an important factor in the development and maintenance of a nitrifier population. The nitrifiers are autotrophic organisms and have a low growth rate. They do not compete effectively with the rapidly growing heterotrophic organisms that depend on the simple carbonaceous organics in the wastewater. If the biochemical oxygen demand (BOD) of the wastewater is high, the heterotrophic population will dominate the available growth sites and nitrification will be eliminated or suppressed. A high suspended solids (SS) concentration in the wastewater also has the same effect (Ericsson 1976). Trace metals and other toxic substances can destroy bacterial growths and the nitrifying bacteria are more susceptable than the heterotrophic type. As discussed above, sufficient alkalinity must be present in the wastewater to avoid inhibition through pH depression. As shown by the general reaction below, nitrification releases hydrogen ions, which in turn will depress the pH unless alkalinity is present to act as a buffer:

$$22NH_4^+ + 37O_2 + 4CO_2 + HCO_3^- \rightarrow C_5H_7O_2N + 21NO_3^- + 20H_2O + 42H^+.$$

Table 2 is a summary of these process requirements for successful nitrification in trickling filter systems. Operational considerations can also influence the effectiveness of the system. Recycling of all or a portion of the filter effluent is a common practice. In some cases, this recycling serves to dilute the strong incoming wastewater; in others, recycling is also necessary during low flow periods to keep the biological film .ist. In either case, recycling in the winter months will serve to lower water temperatures and inhibit nitrification reactions. Increasing the unit hydraulic loading suddenly can also result in washout of the biological film. Schwarz (1976) increased the rate from 0.008 $m^3/min \cdot n^2$ to 0.012 $m^3/min \cdot m^2$ and lost the nitrifiers in a rock media filter.

It is possible that some of the organic nitrogen entering the system will be hydrolized by the heterotrophic bacteria and additional ammonia released to the system. In a study of a plastic media unit, Schwartz (1976) indicates that about 30% of the incoming organic nitrogen was removed, resulting in an average increase of "new" ammonia of about 2.5 mg/L. Some design procedures take this potential increase into account by

Table 2. Process requirements for nitrification in trickling filters.

Requirement	Value
pH	6.6 to 9.0
Temperature	4° to 35°C
Dissolved oxygen	>0.5
BOD	<30 mg/L*
BOD/TKN ratio	1-3
SS	<60 mg/L
Alkalinity	7.14 mg $CaCO_3$/1 mg NH_4^+
Metals and toxics	low concentrations

*Note: This is usually expressed in terms of mass loading for design purposes. To ensure 75% nitrification, the organic loading should be less than 0.35 kg BOD/m^3•d for plastic media, and 0.19 kg BOD/m^3•d for rock media (Harremoes 1982, Stenquist 1974).

recommending that the design be based on the total Kjeldahl nitrogen (TKN) in the incoming wastewater (the TKN is equivalent to the total of organic and ammonia N).

LITERATURE REVIEW

Most of the recent research has focused on plastic media, since the general utilization of this new material has been coincident with the growing concern for nitrogen removal/conversion. Related research has also been directed at "biofilters" of various configurations and at RBC concepts. Some of this work is pertinent since all of these are "attached growth" concepts and the biological responses should be similar.

Stenquist (1974) examined BOD and ammonia nitrogen removal in a 6.6-m-tall plastic media (modular type) trickling filter tower (treating primary effluent) in south-central California. BOD loadings ranged from 0.2 to 3 kg/m^3•d and hydraulic loadings from 0.006 to 0.01 m^3/min•m^2. The influent temperature ranged from 26 to 29°C, pH 6.9 to 7.0, and alkalinity (as $CaCO_3$) from 171 to 244. At BOD loading rates of less than 0.35 kg/m^3•d

Table 3. Nitrification results (after Stenquist 1974).

BOD loading ($kg/m^3 \cdot d$)	Influent (mg/L)		Effluent (mg/L)	
	TKN	NH_3	TKN	NH_3
0.224	27.8	16.5	9.9	1.0
0.352	28.9	17.5	11.0	2.0

they were able to achieve about 94% BOD and 89% ammonia removal in the same filter unit. Table 3 summarizes their results under steady-state operating conditions. A comparison of the input and output nitrogen values in Table 3 indicates that about 2.4 mg/L of "new" ammonia was released by hydrolysis of the organic nitrogen entering the system. This is essentially the same as measured by Schwarz (1976) in the study described in the previous section. Inclusion of the 2.4 mg/L of "new" ammonia means that the overall ammonia removal in the Stenquist study approached 90%. Since water temperatures were never lower than 23°C, no adverse temperature effects were noted in their study. With BOD loading higher than 0.4 $kg/m^3 \cdot d$, sloughing of solids from the media will increase and nitrifiers will be washed out of the system.

Schwarz (1976) examined BOD removal and nitrification in another modular plastic media unit (treating primary effluent) about 7.3 m deep, in Amherst, Mass. The BOD loading was about 2.1 $kg/m^3 \cdot d$ with a hydraulic loading of about 0.08 $m^3/m^2 \cdot min$. Water temperature in the study period ranged from 8° to 23°C. The average BOD removal was 68% and ammonia nitrogen removal about 51%. Figure 2 compares the various forms of nitrogen in this filter unit. It is apparent that the most significant nitrification occurred in the top few meters of the tower. Concurrent BOD and ammonia removal should be expected in a single "combined" tower, although typically nitrification would improve with depth as the BOD loading decreases. This trend is not shown in this experiment. Some factor, possibly sloughing of solids, limited further nitrification in the bottom third of this unit. Ice buildup on the filter surface forced termination of the experiment in January.

Engel et al. (1980) studied performance of a modular plastic media unit (7.2 m deep), treating lagoon effluent in Waldorf, Maryland. The BOD loading was about 0.42 $kg/m^3 \cdot d$ with a hydraulic loading of 0.08 $m^3/m^2 \cdot min$. Water temperature during the 1978 study period ranged from a low of 8°C to

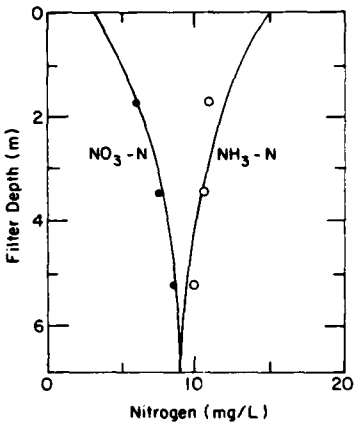

Figure 2. Nitrogen forms in Amherst, Massachusetts, trickling filter (after Schwarz 1976).

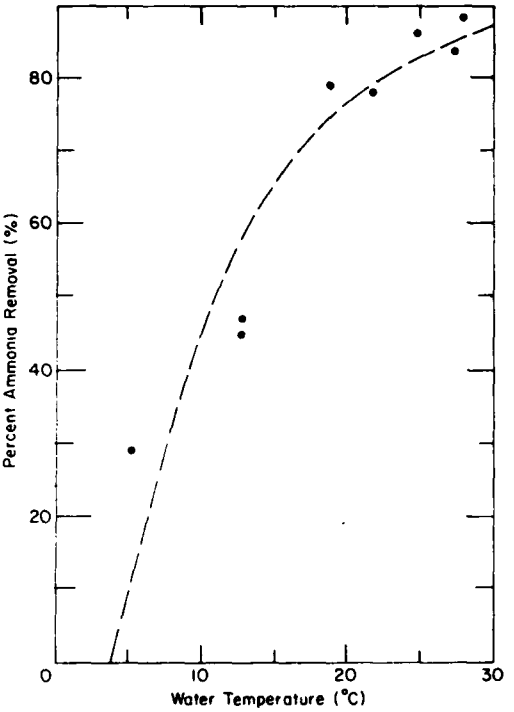

Figure 3. Nitrogen removal vs water temperature in Waldorf, Maryland, trickling filter.

a high of 28°C, with an average of 17.5°C. The median pH was 7.4 and alkalinity (as $CaCO_3$) about 105 mg/L. About 20% of the alkalinity was lost from reactions in the filter but the final pH remained at 7.4. There was essentially no change in BOD or SS concentrations in the water passing through the unit. Ammonia nitrogen removal averaged 77% (low of 47% in April, high of 88% in August). Figure 3 compares these ammonia removal results to the average monthly water temperatures during the study period.

It is apparent from the data that insufficient carbon was in the wastewater to support the heterotrophic organisms, since neither the BOD nor the organic nitrogen concentrations changed. As a result, the autotrophic nitrifiers dominated throughout the entire bed. The ammonia removals experienced in this system were comparable to Stenquist's results in California but the hydraulic loading was almost an order of magnitude higher. In addition, since apparently few heterotrophs were in the Waldorf unit, there should be no production of "new" ammonia from hydrolysis of the organic N, and in fact the organic N concentration did not change. The Waldorf data also suggest little sloughing of the biological films, since the suspended solids concentrations did not change significantly.

Huang et al. (1982) evaluated ammonia removal in the laboratory using pilot-scale (1.8-m-deep) modular plastic media. They carefully metered the applied secondary effluent wastewater flow and controlled the BOD and nitrogen loading on the system. The BOD loadings ranged from 0.6 to 1.5 $kg/m^3 \cdot min$. The pH was in the 7 to 8.0 range, temperature was 20° to 26°C and alkalinity (as $CaCO_3$) 300 to 700 mg/L. Nitrogen loading was controlled by adding ammonia chloride (NH_4Cl) to the wastewater solution as required. Ammonia removals ranged from 87% at the low end of the loading range to 43% at the higher loadings. Their results at the low end were comparable to those of Stenquist (1976) for comparable loading rates, but in this case ammonia removal was achieved within a 1.8-m depth while Stenquist's tower (designed for both BOD and ammonia removal) was 6.6 m tall. Huang et al.'s data, when normalized for flow variations, show that ammonia removal is dependent on ammonia loading (expressed as kg NH_4/m^2 of filter surface) within the range studied.

Duddles et al. (1974) studied ammonia removal in a 6.6-m-tall, modular plastic media, pilot-scale trickling filter unit in Midland, Michigan. Influent for the test period was secondary effluent from the municipal wastewater treatment plant that used conventional rock media trickling filters. The filter influent characteristics were BOD < 20 mg/L, SS < 20 mg/L, pH 7 to 8, organic N < 4 mg/L, NH_3-N 8 to 18 mg/L, and water temperature 7° to 20°C. The hydraulic loading rates ranged from 0.02 $m^3/m^2 \cdot min$ to 0.08 $m^3/m^2 \cdot min$, resulting in a BOD loading ranging from 0.06 to 0.27 $kg/m^3 \cdot d$. At the low end of the loading range ammonia removals were consistently maintained at 80 to 90% over the entire 18-month study period. The nitrification rates decreased with increased loading rates and, as shown in

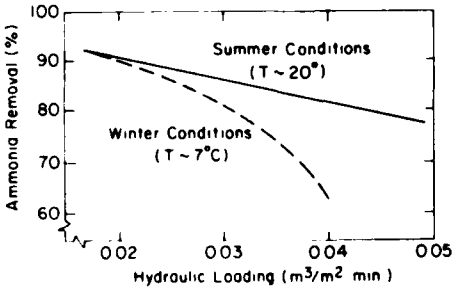

Figure 4. Nitrogen removal in Midland, Michigan, trickling filter (after Duddles et al. 1974).

Figure 4, also with temperature as the loading rate increased. The ammonia conversion with depth in the unit is similar in form to the results shown in Figure 2. In this study, significant removal was essentially complete within the upper 4.5 m. Significant removal of BOD or SS was not noted, indicating again that the nitrifier organisms dominated in the media. The biomass was described as a "thin, tough, grey-brown slime that was resistant to drying and sloughing." This is very different than the growth on conventional trickling filters and combined filters intended for both BOD and ammonia removal. These characteristics suggested that a final clarifier would not be required after this nitrification step.

Based on this study, the following design recommendations were made:

1. Free the waste stream of nitrification inhibitors
2. Keep influent NH_3 below 25 mg/L
3. Keep influent BOD below 0.24 $kg/m^3 \cdot d$
4. Maintain a relatively constant total flow
5. Use application rates as shown in Figure 5
6. Recycle only to maintain biomass.

The city of Lima, Ohio, conducted pilot studies in 1973-74 similar to those described above, and on that basis, designed and constructed full-scale second-stage nitrification trickling filters for their 70,000-m^3/day design flow (Sampayo 1980). The hydraulic loading rate was reported to be

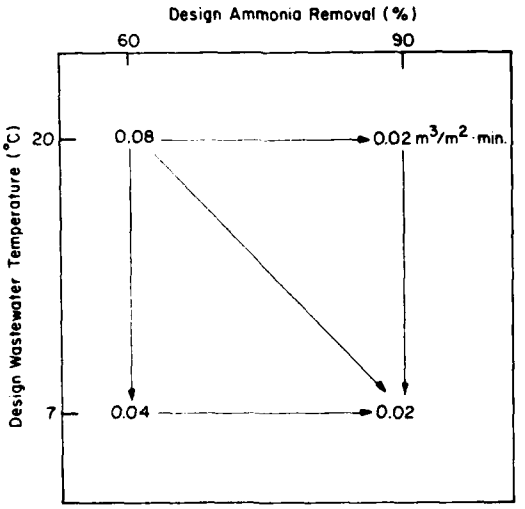

Figure 5. Ammonia removal vs temperature and loading rate (after Duddles et al. 1974).

about 0.03 $m^3/m^2 \cdot min$ on each of Lima's two 6.6-m deep, 32-m-diam filter towers. The BOD loading was estimated to be less than 0.01 $kg/m^3 \cdot d$, based on limited data collected in 1979, well below the levels cited previously for other studies. However, some BOD and organic N removal was reported, suggesting some heterotrophic activity in the filter tower. This system consistently produced a final effluent with 2-3 mg/L of ammonia or less, with liquid temperatures ranging from 9 to 24°C. The ambient air temperatures ranged from 2.4°C in January to 23.2°C in July. Minor surface icing did occur in the coldest months, interfering with rotation of the sprinkler boom. The problem was easily corrected by shutting off the outboard sprinklers that impact on the container wall.

Considerable work has been done on development of design criteria for trickling filters, biofilters, etc., intended for ammonia removal related to fish hatchery and the fish farming business. Design procedures have been developed by Liao and Mayo (1974), Speece (1973) and Cooley (1979). In general these are first-order mathematical models with temperature dependence for ammonia removal described by the van't Hoff-Arrhenius relationship at temperatures above 10°C. George (1982) presents an excellent summary on this topic. Research on RBC units (Brenner et al. 1984) indicates that significant nitrification will not occur until the soluble BOD is reduced to about 15 mg/L to permit the development of the nitrifying organisms on the disk surfaces. Ammonia removal will then proceed at essentially a constant rate of about 1.5 kg $NH_3/1000\ m^2 \cdot d$ down to about 5 mg/L. Removal to levels below 5 mg/L proceeds at a first-order reaction rate. Temperatures above 13°C do not affect performance, but nitrification rates drop significantly below 13°C. Pano and Middlebrooks (1982) reported zero removal at 5°C.

MATERIALS AND METHODS

The research efforts were conducted at the full-scale trickling filter system at Tobyhanna, Pennsylvania, and with two pilot-scale units constructed at CRREL in Hanover, New Hampshire. Since performance of trickling filters varies with the type of media, a special effort was made to obtain, for the pilot-scale units, the same media that were used at Tobyhanna. Data were collected at the Tobyhanna system during the 1982-83 and 1983-84 winters, and for a continuous 250-day period (July 1984 to Feb 1985) at the pilot-scale units in Hanover.

Field work at Tobyhanna

The original conventional rock media trickling filter plant at Tobyhanna was constructed in 1951. Upgrading was required to satisfy more stringent discharge regulations imposed by the State of Pennsylvania. In addition to BOD and SS levels, the permit also required ammonia and phosphorus removal as well as specific limits on 10 different metals. It is assumed that the latter requirements were imposed because metal plating and related activities are part of the industrial operations at Tobyhanna.

The existing primary and secondary clarifiers and the sludge digestor were retained as well as the foundation for the original trickling filter. New construction to meet the new standards included a flow equalization basin, Archimedes screw pumps, two random fill plastic media trickling filter units (4.9 m deep, 18.5 m in diameter), and facilities for chemical removal of phosphorus, effluent filtration and sludge thickening. Figure 1 is a photograph of the Tobyhanna trickling filter units, and Figure 6 is a matic diagram showing the system components of concern to this study. The design capacity of the upgraded system was 3028 m^3/d. As shown on Figure 6, there are dual primary and secondary clarifiers and trickling filters. The piping allows either one or both of the clarifiers to be used and allows the trickling filter units to be operated separately, in series or parallel. One filter bed and all other components were operated in the

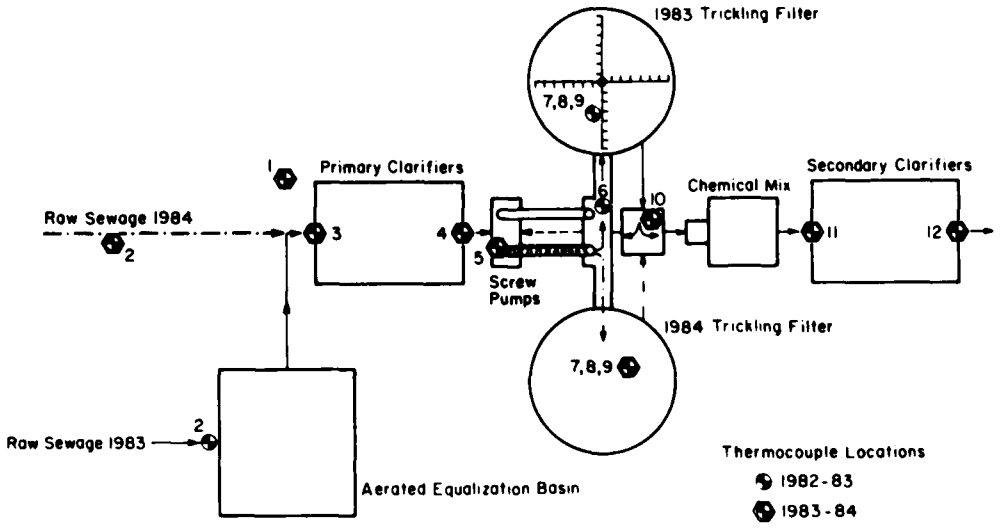

Figure 6. Treatment plant layout at Tobyhanna Army Depot, Pennsylvania (no scale).

Table 4. Performance expectations and raw sewage characteristics, Tobyhanna, Pennsylvania.

Parameter	Raw sewage (mg/L)	Final effluent (mg/L)
BOD	90	10
SS	125	15
Ammonia (as N)	15	3 (June-Oct) 9 (Nov-May)

1982-83 test period. The equalization basin was bypassed during the 1983-84 winter and both trickling filter units operated in series until severe icing problems occurred.

Each of the trickling filters was designed for concurrent BOD and ammonia removal as a "combined" unit, and was sized using criteria from the media manufacturer. Ammonia removals to the specified levels were expected at the full 3028-m^3/d design flow. Table 4 compares performance requirements for the entire system to raw sewage characteristics for the parameters of concern to this study. Other components in the system contribute to BOD and SS removal but the trickling filter is the only element responsible for significant ammonia removal. Recycling rates on the trickling filters are also adjustable, and for both study periods the recycling was equivalent to about 75% of the daily flow.

Copper-constantan thermocouples were installed by CRREL staff in 1982-83 and 1983-84 at the points shown on Figure 6. The three thermocouples (7, 8, 9) shown in Figure 6 were installed at the media surface, and at depths of 30 and 60 cm in the trickling filter bed. Thermocouple 10, in the recycle pit, measured the temperature of the effluent from the trickling filter. These thermocouples were connected to a Kaye Digestrip III automatic data logger programmed to record all temperatures (°C) once per hour. A totalizing anemometer was installed near point 1 (in Fig. 6) to record average daily windspeed. Data on flow rates, water quality parameters, etc., were routinely collected by the Tobyhanna facility engineering staff. The temperature data covered the periods of 11 February to 9 March 1983 and 29 February to 15 March 1984.

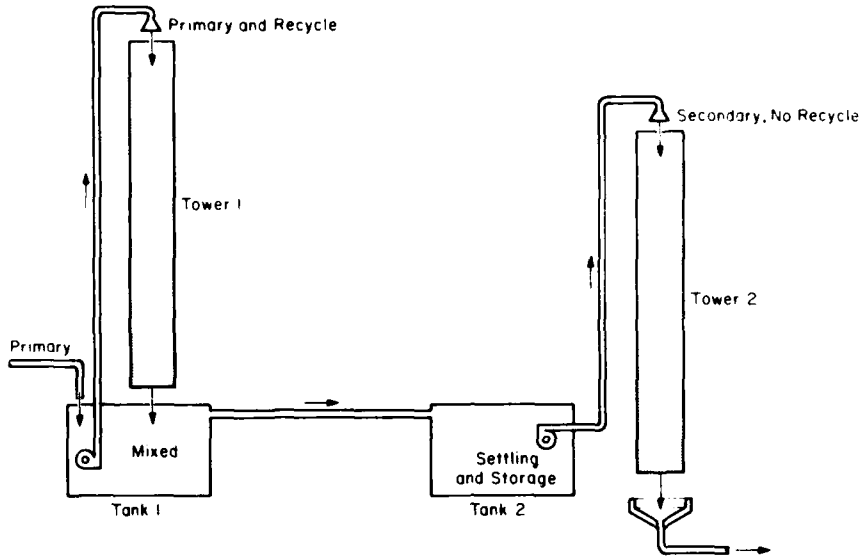

Figure 7. Flow diagram for pilot units at Hanover, N.H.

Pilot-scale work at Hanover

It was the intent of the pilot tests in Hanover, N.H., to compare performance of a "combined" unit designed for both BOD and ammonia removal to a single purpose unit designed for just ammonia removal from low solids secondary effluent. This was made possible by the special features of the Hanover system, shown schematically on Figure 7. The "combined" unit (tower 1) is mounted directly over a holding tank. Primary treated wastewater enters the holding tank and is mixed with the contents by a circulating pump. A second pump lifts this liquid to a spray nozzle on top of the trickling filter. The applied liquid drains through the filter back into the holding tank where it is remixed and portion reapplied to model recycling on a trickling filter unit designed for combined BOD removal and ammonia conversion.

The entering primary wastewater displaces an equivalent volume of treated mixture that flows to a second holding tank. This second tank was intended to perform as a clarifier and allow solids to settle. The clarified liquid was then pumped to the spray nozzle on top of the second filter unit (tower 2). Recycling was not included in this second unit. Both of the distribution pumps were of variable speed and positive displacement, which allowed direct control of the hydraulic loading on each filter tower. An in-line totalizing flow meter was placed downstream of each pump.

The two trickling filter towers utilized in this study were constructed from steel culvert tubes 4.2 m long and 0.6 m in diameter. Each of these culverts was insulated with 1.3 cm Armourflex insulation. Sample ports, and thermocouple ports, 3 cm in diameter, were drilled at 0.6-m intervals from the bottom of both towers. The towers were then filled with the plastic filter media to a level 0.6-m from the top, such that the topmost sample port was located at 0.6-m depth into the media.

Each of the sample ports was equipped with a 20-cm-long PVC sampling tube. The sample tubes had an o.d. of 2.5 cm and were cut lengthwise for about 20 cm to form a catch tray. The tubes were inserted into the tower so that the tray end of the tube could be used to catch water flowing down the tower. Flow from the tubes could be stopped simply by rotating the tube such that the tray faced down. Sample ports were sealed around the rim with rubber grommets attached to the tubes with hose clamps. Each sam-

Figure 8. Sample ports in pilot filter at Hanover, N.H.

Figure 9. Plastic media used in full-scale unit at Tobyhanna Army Depot, Pennsylvania, and in pilot-scale unit at Hanover, N.H.

ple port was staggered from the others in such a way as to prevent one tube from dripping down on a lower port and causing sample contamination.

The thermocouple ports were located at points 45° from the sample ports. Thermocouples were taped to wooden dowels, and inserted into the tower approximately 2.5 to 5 cm from the center. Each thermocouple was wired into a Kaye system 8000 datalogger. All plumbing in the system was 2.5-cm-i.d. copper with a tap valve installed to provide samples of applicant on each of the towers when needed. This piping was insulated and heat traced to permit winter operations.

The photograph on the cover of this report shows the Hanover pilot system during construction. Figure 8 shows the sampling ports in operation and Figure 9 shows the plastic rings used as media in both towers and in the full-scale Tobyhanna system. The ring is about 19 cm in diameter and 5 cm deep.

Samples were routinely taken during select periods from the input flow and from the sampling ports in each tower. Temperatures were monitored continuously during each sampling period. Flow into the system and onto the towers was monitored daily. This approach allowed evaluation of performance with respect to depth in the tower and temperature. The samples were processed in the CRREL lab for BOD, pH, ammonia nitrogen and nitrate nitrogen using the following procedures.

BOD

Samples were analyzed for BOD using the 5-day membrane electrode method as outlined in the 15th edition of Standard Methods for the Examination of Water and Wastewater, sections 507 and 421F. For soluble BOD, the filtrate of a sample, passed through an AP40 Millipore prefilter, was analyzed in the same manner. Dilution determination for each sample was based on most recent BOD data results. Details of specific procedural methods, modifications and equipment can be found in U.S. Environmental Protection Agency (1985).

pH

The sample pH was determined using a Markson 1808 Polymark pH probe and a Markson Selectromark Analyzer (series 4500) with automatic temperature control. Details of procedure may be found in Butler (1985).

Ammonia

These determinations employed an Orion ammonia electrode, model 95-12, with an Orion 811 microprocessor pH/mV meter. The procedure was as stated in the probe's instruction manual. Briefly, the millivolt readings produced by three standards (0, 10 and 100 mg/L) were recorded and graphed on semi-log paper. The samples' millivolt readings were then measured and recorded. The number of milligrams per liter of NH_3-N in the samples was then determined from the previously plotted standards. There are many procedural specifics that must be followed, all of which are explained in the ammonia probe instruction manual.

Two important points should be noted:

1. The samples and standards must be at the same temperature. A 1°C difference will result in a 2% measurement error. To avoid temperature differences, we poured the samples into test flasks as soon as they were received, and immediately sealed them tightly with parafilm. Samples, standards, NaOH (used in the procedure) and milli-Q water used to rinse the probe were then allowed to come to room temperature before millivolt readings were taken (approximately 4 hours - especially in winter).

2. Care must be taken not to use soap, which might contain ammonia. All glassware we used was initially acid washed in a 1 N HCl solution, and then rinsed with distilled water after each determination.

Nitrates

The Hach low range nitrate test kit, model NI-14, was used for nitrate nitrogen determinations. Descriptions of methods used are included in the kit. The 0 to 1-mg/L range was used for primary effluent samples; the 0 to 10-mg/L range was used for all other samples. This procedure is a simplified cadmium reduction method in which the sample is shaken for 3 min with a cadmium compound (Nitra Ver VI nitrate reagent), allowed to settle, transferred, shaken for 30 seconds after a color reagent (Nitra Ver III NO_2 reagent) is added, and left for at least 10 minutes to allow full color development. The nitrate nitrogen measurement is then determined using the color comparator included in the kit.

RESULTS AND ANALYSIS

Water quality data provided by the Tobyhanna Facility Engineer indicated that the system generally satisfied discharge requirements for BOD, SS and phosphorus on a routine basis. The BOD did, however, exceed specified limits at times during January and February 1982. The ammonia nitrogen exceeded the 9 mg/L winter limit for most of the 1981-82 winter and only satisfied the 3 mg/L warm season limit during June and July of 1982. These responses indicate that a combination of factors may be responsible for the performance. In addition to temperature inhibitions in the winter, the 1981-82 winter data on many occasions indicate a higher ammonia concentration in the effluent than was present in the incoming wastewater. This release of "new" ammonia indicates that hydrolysis of organic N was occurring in either the aerated equalization basin or the trickling filter. It was therefore probable that the heterotrophic organisms dominated the system and significant ammonia conversion could not occur. Another possibility is the spill or leakage of metals or other toxics from the industrial type operations at Tobyhanna Depot. This would adversely affect the nitrifiers and the unit would then require time to recover, particularly in the winter.

The ammonia removal performance during the 1982-83 winter at Tobyhanna was similar to that described above. The average hydraulic loading was 0.005 $m^3/m^2 \cdot min$ and the BOD loading was estimated at 0.038 $kg/m^3 \cdot d$ during this period. These are within the range recommended by the manufacturer of the media used (0.004 to 0.06 $m^3/m^2 \cdot min$) and well below the loading rates

cited for the successfully operating systems discussed in the literature review section of this report. All of the systems discussed in the literature that successfully nitrify in the winter months in cold climates are single purpose units designed only for ammonia conversion of treated effluent. Performance of the Tobyhanna system may therefore be constrained by a combination of low temperature, interference from the heterotrophic organisms and the possibility of periodic low level toxic disruptions. The 1983-84 field work at Tobyhanna and the pilot scale tests in Hanover were intended to separate these variables.

Performance at Tobyhanna

All of the process components shown on Figure 6 were operational during the 1982-83 winter. The average daily temperatures measured at the critical points in the system during this study period are presented in Table A1 of Appendix A. The average actual flow was about 37% of the design flow. On weekends the actual flow dropped to less than 15% of the design rate. A direct result of this low flow is to increase the detention time in each of the process units in the treatment systems. At the design flow the calculated detention time in the system would be about 18 hours. At the average flow experienced in 1982-83, the calculated detention time was 44 hours. This increased exposure results in very high heat losses, and ice formation was a problem in almost all components in 1982-83.

Table 5. Temperature and heat losses, Tobyhanna, Pennsylvania, February-March 1983.

Process unit	Temperature loss (°C)			Heat loss (%)
	Maximum	Minimum	Mean	
Equalization basin	7.7	1.1	3.3	47
Primary clarifier	1.8	0.1	0.5	7
Pump pit*	5.8	0.4	2.4	1
Trickling filter	1.0	0.2	0.4	38
Secondary clarifier	1.6	0.2	0.5	7
Total	17.8	2.0	7.1	100

*Includes recirculation effect since a portion (75%) of trickling filter effluent is returned to this pit.

The average temperature and proportional heat losses, calculated from the thermocouple data, are summarized in Table 5. The major heat losses occurred at the equalization basin and in the trickling filter. A thermal analysis of the latter indicates convection and radiation losses from the exposed top surface of the filter (Reed et al. 1984). The net result, as shown on Table A1, was to have liquid temperatures in the trickling filter at, or very close to, the threshold values for nitrification. Assuming all other conditions were favorable, these very low temperatures would still eliminate the potential for significant nitrification.

A comparison of the temperature data indicates that most of the heat loss in the trickling filter occurred within the top 60 cm. Since liquid flow is unsaturated in the bed, the thermocouple is sensing both the air and liquid film temperatures at the measurement point. A regression analysis of selected data pairs produces the following relationships:

$$T_0 = 5.70 + (0.44)(T_A) \quad [r^2 = 0.87] \tag{1}$$

$$T_{60} = 2.94 + (0.74)(T_0) \quad [r^2 = 0.90] \tag{2}$$

$$T_E = 2.81 + (0.57)(T_0) \quad [r^2 = 0.87] \tag{3}$$

where

T_{60} = average daily temperature at a depth of 60 cm in filter, °C

T_A = average daily air temperature at site, °C

T_0 = average temperature at surface of trickling filter, °C

T_E = average temperature of effluent from trickling filter.

It can be shown with these equations, for the flow conditions observed, that a temperature at the bed surface of 7.3°C would be required to sustain desirable (7°C) nitrification temperatures throughout the filter bed. Adding the temperature losses in the other units indicates that the average raw sewage temperature would have to be at least 13.6°C to maintain acceptable conditions in the trickling filter. Such temperatures did not exist at any time in the 1982-83 study period, so it is not surprising that ammonia conversion did not occur.

Several operational changes were made for the 1983-84 winter in an attempt to improve the thermal conditions and the ammonia conversion capability of the system. The equalization basin and one of the primary clarifiers were bypassed, and starting in late November, the two trickling

Table 6. Average temperature comparisons for Tobyhanna, Pennsylvania.

Location	Average temperature* (°C) 1983	1984
Air		
Maximum	4.6	-2.0
Minimum	-6.7	-12.3
Mean	-1.8	-7.3
Raw sewage	12.1	14.1
Primary effluent	8.0	11.8
Trickling filter		
Top of bed	2.5	2.7
60 cm deep in bed	4.1	4.9
Effluent	4.8	5.0

*Averages for comparable number of days in each year, during the test periods.

filters were operated in series to see if ammonia removal improved. Table 6 compares the average temperature conditions for the two study periods. The ambient air temperatures were significantly lower in 1983-84, but the raw sewage and the trickling filter were slightly warmer because of the heat conserved through bypassing the equalization basin. Most of the heat losses (87%) observed in 1983-84 occurred in the trickling filter.

Table A2 in Appendix A presents ammonia data collected by the Tobyhanna staff during the 1983-84 winter. Since the wastewater ammonia averaged 32 mg/L during the period, the required removal to reach the 9-mg/L discharge limit would be 72%. The average removal with the two filter units in series was 70%; with a single unit in operation the removal only averaged 62%. Performance did improve with the two units in series, but not enough to reliably satisfy discharge requirements. Had the series operation been started in warm weather, ammonia removal would probably have been better. However, icing problems would still have forced termination of the series operation in December. Figure 10 shows the ammonia removal achieved versus air temperature during this test period.

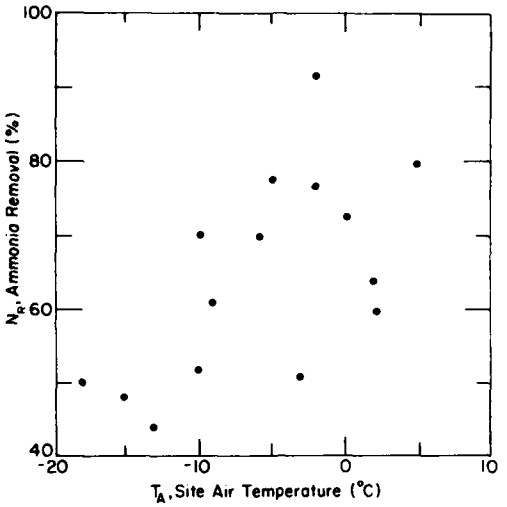

Figure 10. Ammonia removal vs temperature in Tobyhanna Army Depot unit, November 1983 to 20 February 1984.

The thermal analysis indicates that temperatures in the filter bed would be unsuitable for nitrification about 75% of the time in the coldest design year, under the present operational conditions (Pano and Middlebrooks 1982). We recommended that the filter units be covered to sustain desired conditions and to avoid icing problems on the media surface. Heat retention will be further optimized by reducing both the recycling of effluent and the counter-current air flow to the minimum during the winter.

Reducing recycling will be difficult at Tobyhanna because the present average flow is about one-third the design capacity and the current hydraulic loading on the filter, with recycling included, is close to the minimum levels recommended by the manufacturer to keep the media wet. In some cases, it is possible to close off some of the sprinklers and apply wastewater to a smaller surface area on the filter. However, the sprinkler booms at Tobyhanna rotate as a response to the water jets from the sprinklers. Shutting down the outboard sprinklers would reduce, or might even stop, the boom rotation. An external power source or some other method of distribution would then be needed.

Performance of Hanover pilot units

The pilot units in Hanover, N.H., used the same random fill, plastic media (see Fig. 9) that were used in the full-scale system in Tobyhanna.

The media manufacturers' criteria were used for design to ensure comparable systems. Treatment in such units is actually a function of the detention time in contact with the biological layer on the media surface. Since that value is difficult to quantify, other more indirect, but more easily quantified, criteria are commonly used for design.

The design hydraulic loading is typically expressed in terms of the water volume applied per unit area for the total surface area at the top of the filter. The removal of BOD and ammonia are dependent on the available surface area on the media itself. This "specific surface area" depends on the media configuration and ranges from about 90 m^2/m^3 to over 200 m^2 of surface area per 1 m^3 of media volume. The media used in these tests are rated at 102 m^2/m^3 by the manufacturer. A minimum hydraulic loading rate is often specified to ensure that most of this potential area is wetted, and therefore functional. A simplification is possible for particular media, and BOD loading is often expressed in terms of the daily mass loading per unit volume of the media. It is more common to relate ammonia removal to specific surface area of the media so that loadings are expressed in terms of the daily mass of ammonia per unit area of the "specific surface area." Some confusion can result since both ammonia and the hydraulic loadings are expressed in terms of a unit area, but the area involved is not the same.

The diameter of the CRREL units was 0.6 m and was selected for convenience to keep the required hydraulic loading within reasonable limits. The first tower was designed as a combined unit for both BOD and NH_4 removal. The design flow was about 3.8 m^3/day of primary effluent with recycling adjustable up to about 100%. Based on the known wastewater characteristics, calculations with the manufacturer's criteria indicated that a 2-m depth in the tower would be required for BOD removal, and another 0.8 m of depth for ammonia conversion. The "treatment zone" to be monitored was set at 3 m and a sampling port installed at that depth. Other ports were installed, as described previously, at regular intervals between that point and the top surface of the media. The second tower was intended to model a single purpose filter designed for nitrification of clarified, secondary effluent. The second tower was identical in configuration and dimension to the first. Based on the preliminary calculations it was expected that the entire depth of the second tower would be effective for ammonia removal.

Data collection started in July 1984 and continued through February 1985. Air temperature and flow were monitored on a daily basis. Tests for BOD, NH_4, NO_3 and pH were run on influent and effluent during selected periods, which represented different temperature conditions. Internal temperatures and ammonia removal within the two towers were also monitored on a selected basis. Water quality data were not collected in October and December, because malfunctions with system pumps made it difficult to sustain a uniform application. There was sufficient water to keep the units wet but the flow was too variable to sustain steady-state conditions. All of the pertinent ammonia data are in Table A3 of Appendix A. There is considerable daily variation in these results on a daily basis due to wastewater composition, temperature changes, and to minor variability in the daily pumping rates. Trends are not apparent until the data are averaged on a monthly basis; these results are presented in Table 7. The corresponding hydraulic, BOD and ammonia loadings for both towers are compared to Tobyhanna in Table 8. Several BOD samples, both filtered (soluble BOD) and unfiltered (total BOD), were tested because design approaches for trickling filters are based on only the dissolved BOD fraction. A summary of temperature results is given in Table 9. These are the 24-hr average

Table 7. Summary of data - Hanover pilot units.

Month	Air temperature (°C)	Tower 1			Tower 2	
		Flow* (m^3/d)	Recycle (%)	NH_4 removal (%)	Flow (m^3/d)	NH_4 removal (%)
July	20	6.93	84	28	2.74	36
August	21	6.36	43	28	4.52	55
Sept.	14	5.86	40	12	3.09	30
Nov.	1.0	6.56	74	4	3.27	7
Jan.	-8.9	6.84	1.05	4	2.05	2
Feb.	-4.7	6.57	76	3	2.85	†
	Average	6.52	54		3.08	

*Includes recycle.
†A freeze-up in piping system forced shut-down of tower 2 in early February.

Table 8. Average loading values - Hanover pilot units and full-scale Tobyhanna system.

Parameter	Hanover tower 1 w/recycle	Tobyhanna full-scale w/recycle	Hanover tower 2 w/o recycle
Hydraulic load ($m^3/m^2 \cdot min$)*	0.016	0.005	0.007
BOD_5 (total)† (kg/d)	0.826	--	0.223
(dissolved)** (kg/d)	0.111	--	0.037
BOD_5 (total)†† ($kg/m^3 \cdot d$)	0.44	0.08	0.12
(dissolved) ($kg/m^3 \cdot d$)	0.06	--	0.02
Ammonia kg/d	0.124		0.006
($kg/m^2 \cdot d$)***	6.6×10^{-4}	6.1×10^{-4}	3.2×10^{-5}

*Hydraulic load is related to total area at top of filter (m^2) and includes recycle if recycle is used.

†Total BOD_5 is standard test on unfiltered sample.

**Dissolved BOD_5 is standard test on filtered sample.

††BOD loading is in terms of total volume of filter media (m^3).

***Ammonia loading is in terms of the specific media surface for the media used in the units (102 m^2/m^3).

Table 9. Temperature data - Hanover pilot units.

24-hr average air temperature	24-hr average temperature (0.5-to 2.5-m depth)	
	Tower 1	Tower 2
°C	°C	°C
12.1	9.5	9.6
9.2	8.6	-*
1.2	8.1	8.4
-0.5	7.8	7.1
-14.2	4.2	3.8

*Pump malfunction this day, so internal temperatures are not representative.

temperatures as measured by thermocouples inside each tower and in the immediately adjacent ambient air. Typical plots of these temperature data are shown in Figures 11 and 12, to represent a "warm" and a "cold" period. Each plot shows the average 24-hr temperature as well as the range experienced during the period. In both cases there is a slight cooling trend

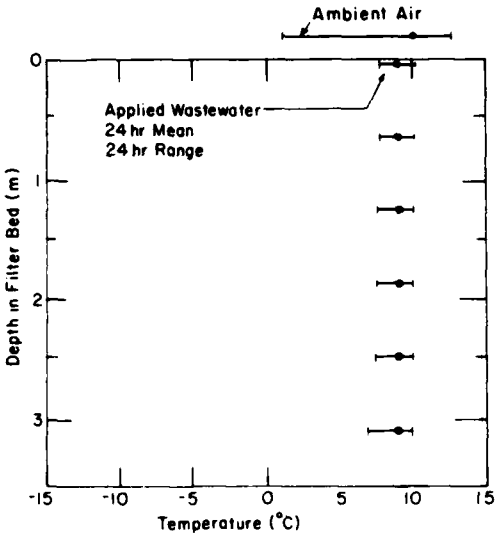

Figure 11. Temperature vs depth in tower 1 of the pilot-scale unit at Hanover, New Hampshire, for a warm period.

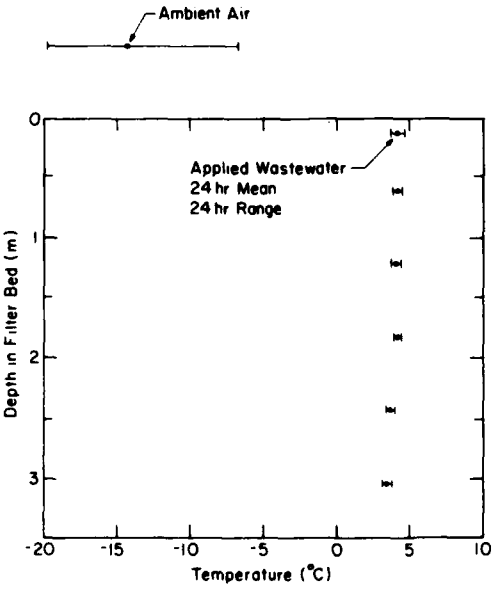

Figure 12. Temperature vs depth in tower 1 of the pilot-scale unit at Hanover, New Hampshire, for a cold period.

with depth. Comparison of the plots indicates the internal temperature changed only about 5°C while the ambient air changed at least 20°C. The internal temperatures shown on Figure 12 would, according to the theory, be too low to sustain nitrification, and the ammonia removal was zero as indicated by the tests on that day.

An equation relating temperature in the treatment zone of the towers to the ambient air temperature was developed from the data in Table 9:

$$T_T = 7.31 + 0.21\ T_A \qquad [r^2 = 0.96] \qquad (4)$$

where T_T is the average daily temperature within the treatment zone (0.5-2.5 m), °C, and T_A is the average daily air temperature at the site, °C. This is very similar to eq 1 derived for the full-scale units at Tobyhanna.

The ammonia concentration, with depth, is compared in Figure 13 for both the Hanover units when internal tower temperatures were about 13°C. Tower 2 clearly indicates a higher ammonia removal, with the entire depth contributing significantly. Tower 1 shows much lower removals but also has a trend toward continuing removal with depth. This lends support to the hypothesis that BOD and SS may interfere with ammonia removal in "combined" systems. The hydraulic loading was lower on tower 2 than on tower 1 when the recycling is considered, so the residence time in tower 2 was longer

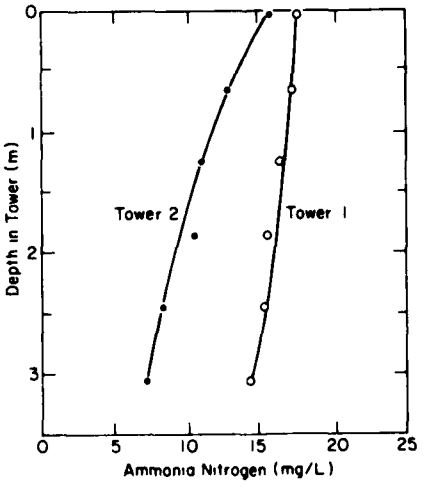

Figure 13. Nitrogen removal vs depth in towers 1 and 2 of the pilot-scale unit at Hanover, N.H.; water temperature 13°C.

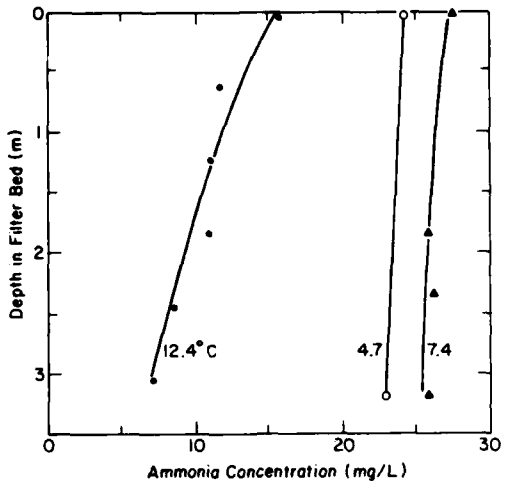

Figure 14. Ammonia concentration vs depth in filter tower 2 of the pilot-scale unit at Hanover, N.H. Temperatures are for mid-zone in the filter bed.

and possibly contributed to improved overall efficiency. However, the difference in hydraulic loading is not as great as the differences in ammonia concentration shown in Figure 13.

Figure 14 demonstrates the effect of temperature on ammonia removal within trickling filter tower 2. At the 12.4°C temperature, the overall removal was about 55%. At the 7.4°C temperature, the removal was about 5%. At the lowest temperature (4.7°C), there was essentially no removal. These are the internal temperatures in the filter tower and were either measured or calculated with eq 4 for this purpose.

An equation relating effluent ammonia to internal tower temperatures was developed using the data summarized in Table 7 for tower 2:

$$\frac{N_e}{N_o} = 1.98\, e^{-0.115\, T_T} \qquad [r^2 = 0.92] \qquad (5)$$

where N_e is the effluent ammonia at (mg/L) at 3-m depth, and N_o is the ammonia in applied wastewater (mg/L). It should be noted that N_e/N_o is the percentage of ammonia remaining in effluent so that

$$\% \text{ ammonia removal} = \left(1 - \frac{N_e}{N_o}\right)$$

$$= 1 - 1.98\, e^{-0.115\, T_T} .$$

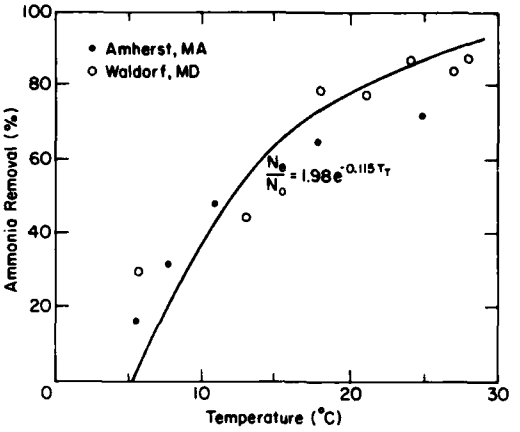

Figure 15. Comparison of ammonia removal vs temperature data from pilot-scale units in Hanover, N.H. and elsewhere.

Equation 5 is only valid for the media and loading conditions used in the Hanover pilot unit, and should not be used for design. However, as shown in Figure 15, this equation compares favorably to the results of other pilot scale studies conducted in Waldorf, Maryland, and Amherst, Massachusetts (Engel and Schwig 1980, Schwarz 1976), although the latter two were deeper units.

It was not possible to develop a similar equation for the results from tower 1 in the Hanover system. There were no clear trends apparent in the tower 1 results, indicating that some factor other than temperature was also influencing ammonia removal.

Hanover-Tobyhanna comparisons

The temperature dependence in the Hanover unit as described by eq 5 indicates a much stronger response to temperature than indicated by the limited data collected at the full-scale Tobyhanna system (Fig. 10). The validity of eq 5 is supported by the comparison to other pilot tests as shown in Figure 15. Either the Tobyhanna data are questionable or some other factor limits the validity of the pilot scale tests.

A possible limitation is related to the relatively small diameter of the Hanover units. Although the thermocouples measured the temperature near the central axis of the unit, the temperatures were probably much lower around the periphery of the unit so that ammonia removal in this zone

would be correspondingly lower. This zone constitutes a much larger proportion of the total area in a pilot unit than in a full-scale system. As a result, the overall ammonia removal measured in the pilot could be less than might be expected at the indicated temperature.

Although significant removal is demonstrated by the Tobyhanna data, the system still could not satisfy design requirements even when the two filters were operated in series. These results and the Hanover data both suggest that the BOD and SS in a combined treatment unit reduce nitrification efficiency, particularly at low winter temperatures. If significant ammonia conversion is a winter requirement, then a separate trickling filter tower should be provided for that purpose. The experience at Tobyhanna and the Hanover results indicate that a combined BOD/ammonia unit will not function reliably for both purposes at low temperatures.

The results from both locations confirm the requirement for a temperature of at least 7°C in the liquid and in the reactor for significant nitrification. The system at Tobyhanna was so lightly loaded in the 1983-84 study period (Table 8) that both units could have been considered as single-purpose nitrification towers. Their performance, however, even in series, fell far short of those expectations. Had the units been covered to retain heat, it is likely that ammonia removal would have improved. When the Tobyhanna system reaches design capacity it will not be possible to run the towers in series since both will be required to achieve the design BOD removal. Prior to that time, a separate, covered trickling filter unit, designed only for nitrification, may be necessary if the effluent standards remain at 9 mg/L.

There is no evidence in either location that any toxic substances interfered with the nitrifiers. Such an occurrence is very unlikely in the Hanover system since the wastewater is entirely domestic. It is also unlikely that the ammonia removals shown in Figure 10 for Tobyhanna could have been realized after a toxic interference, although the potential is still a concern for all locations. If a toxic interference occurs just prior to or during winter, it is unlikely that the nitrifiers could recover because of the low temperature conditions.

DESIGN IMPLICATIONS

Results from the full-scale system at Lima, Ohio (Sampayo 1980), and the tests at Midland, Michigan (Duddles et al. 1974), are compared in

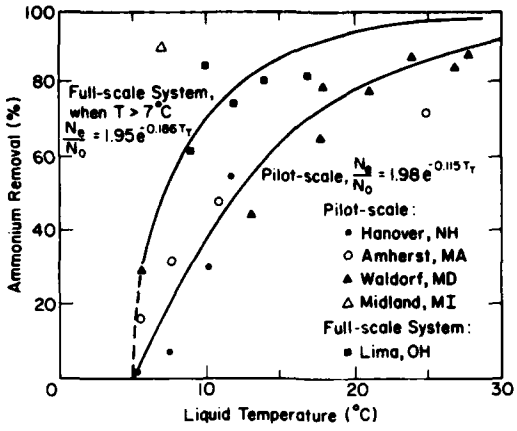

Figure 16. Comparison of ammonia removal vs temperature data from full-scale and pilot-scale units.

Figure 16 to the Hanover and other pilot scale results discussed previously. The pilot-scale unit at Midland, Michigan, shows better removal at 7°C than the full-scale system at Lima, Ohio. In contrast, the pilot-scale results from Hanover, Waldorf and Amherst overestimate the influence of temperature on ammonia removal as compared to the full-scale results. The unit at Lima has about twice the depth of the pilot unit at Hanover, but so do the pilot units in Waldorf and Amherst. Probably almost the full depth may be effective at Lima, Hanover and Midland, but not at the other two pilot study sites. The full-scale system results can be adequately described with eq 6 for treatment temperatures at 7°C and above:

$$\frac{N_e}{N_o} = 1.95\ e^{-0.186T} \qquad (6)$$

A smooth transition to zero removal at 5°C is suggested for temperatures below 7°C, as shown in Figure 16.

The results from Midland (Duddles et al. 1974), as shown in Figures 4, 5 and 16, have become the national design standard for ammonia removal in trickling filter units. Design charts, similar to Figure 17, appear in almost all the literature from the media manufacturers, often without any indication that these are pilot-scale results and also without any indication that the pilot-scale units were for a single purpose, intended for nitrification of clarified secondary effluent. The "combined" system at Tobyhanna was designed from such a chart.

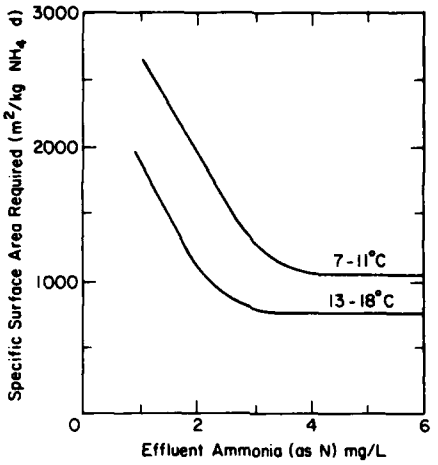

Figure 17. Typical design chart for ammonia removal.

It may be that the Midland, Michigan, results represent the optimum ammonia conversion attainable under carefully controlled conditions. Equation 6 provides a reasonable estimate for full-scale operations and is recommended for future use.

An alternative approach is presented in the new EPA Process Design Manual for Nitrogen Control (U.S. Environmental Protection Agency, in press). This graphical method, derived from the same Lima data, relates ammonia nitrogen in the system effluent to the mass of TKN applied per day per 1000 m^2 of specific media surface. As indicated previously, the Lima system did experience some hydrolysis of TKN, so TKN was chosen as the loading parameter instead of ammonia. An independent analysis, for this study of the same data, produces the following equations:

For summer conditions,

$$TKN = 1.34\ e^{0.009N_e} \tag{7}$$

where TKN is the total Kjeldhal nitrogen that can be applied (kg/d•1000 m^2 of specific surface), and N_e is the effluent ammonia concentration required by the system design (mg/L).

For winter conditions, water and treatment zone in filter bed > 7°C,

$$TKN = 0.892\ e^{0.09N_e} \tag{8}$$

Either equation is entered with the allowable effluent ammonia concentration for the period of concern and the TKN requirements are calculated. The volume of media required can then be determined for a particular type

of media. In most situations summer is the critical period because fish will be most susceptible to ammonia toxicity. The summer discharge limits are therefore usually more stringent than those for the winter period. For these cases, eq 7 should be solved first to determine the design loading, and the resulting value used in eq 8 to verify that winter requirements can also be satisfied. If the same standard prevails on a year-round basis, then eq 8 will control design in cold climates. Equations 7 and 8 should be valid within the range of the other process requirements given in Table 2.

As a general rule of thumb, we suggest that a thermal analysis be conducted as a routine part of design for North American systems above the 38th parallel so that the necessary 7°C temperature can be sustained in the filter bed. A cover will be required for many cases.

CONCLUSIONS AND RECOMMENDATIONS

1. Ammonia removal in a trickling filter is possible under winter conditions as long as the liquid and the treatment zone in the filter bed are maintained at 7°C or greater. In many cases this will require a roof or cover on the filter unit.

2. The presence of BOD and suspended solids (SS) can interfere with the biological nitrification responses. If high levels of ammonia removal are required during the winter in cold climates, a separate, single purpose trickling filter dedicated for nitrification is necessary to ensure reliable performance on a sustained basis.

3. The biological organisms responsible for nitrification are susceptible to toxic interference and to stresses imposed by sudden changes in loading rates or operational conditions. All of these factors require special consideration to ensure reliable low temperature performance. Startup of units in warm weather is a process necessity.

4. The design of single purpose, nitrification trickling filter units can be based on eq 6 to define temperature responses and on eq 7 and 8 to determine the volume of media required. Since so much scatter is in all of the data, the addition of a "safety factor" to the results of eq 7 and 8 is recommended.

5. Based on the experience in Tobyhanna, it is clear that trickling filter units should not be designed for some ultimate flow capacity that

may never be realized. The low flow conditions in oversized units reduce treatment efficiencies and require extra recycling. The extra recycling in turn reduces temperatures and compounds the other problems. If design for ultimate flow is a project requirement, then multiple units should be designed and only brought on line as required.

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APPENDIX A. TEST DATA

Table A1. Tobyhanna, Pennsylvania; 24-hr mean temperature and flow data.

Date	Flow (m^3/day)	Temperature (°C) Air	Filter influent	60 cm deep in filter bed	Filter effluent
Feb 1983					
11	1590	-12.2	2.6	-4.1	1.9
12	984	-8.4	1.3	-2.0	0.9
13	455	-5.8	0.9	-0.1	0.6
14	1211	3.8	3.8	3.1	3.1
15	1192	-1.4	5.9	5.2	5.4
16	2195	0.5	7.1	6.8	6.6
17	1703	1.6	7.4	7.1	7.0
18	992	0.6	6.5	5.5	5.7
19	643	2.7	6.6	6.3	6.4
20	507	-0.1	5.3	5.1	5.1
21	545	3.7	5.8	5.8	5.8
22	878	4.0	7.6	7.5	7.5
23	1026	1.6	7.6	7.7	7.1
24	1404	-1.0	6.5	-	5.6
25	1033	-2.2	6.7	6.1	6.1
26	905	-7.8	2.5	1.4	1.5
27	1094	-2.7	3.4	3.0	2.9
28	1007	1.7	6.6	6.6	6.3
March					
1	889	3.4	8.1	7.9	7.8
2	1241	3.9	7.6	7.2	7.1
3	1207	3.3	7.5	7.2	6.8
4	1390	4.7	8.3	8.4	8.4
5	1430	4.4	8.7	8.5	8.5
6	1177	2.3	7.3	7.2	7.0
7	1230	4.1	8.2	7.7	7.8
8	1340	-0.3	6.2	5.5	5.6

Table A2. Ammonia removal; Tobyhanna trickling filter.

Date	Air temperature (°C)	Ammonia nitrogen (mg/L) Influent	Effluent	Removal (%)
Nov 9*	-3	33	16	51
16	5	34	5	85
23†	2	40	16	60
30	-2	32	8	75
Dec 7	-2	58	4	93
14	-15	35	18	49
28**	-5	20	4	80
Jan 4	0	38	10	74
11	-9	18	7	61
18	-10	38	18	53
25	2	28	10	64
Feb 1	-18	34	17	50
8	-13	27	15	44
15	-11	13	8	38
22	-6	41	12	71
29	-10	33	10	70

* One tower in operation at start of test period.
† Start series (2 towers) operation on 11/18/83.
** End series operation on 12/21/83, only one tower in service for balance of test period.

Table A3. CRREL pilot studies; ammonia data.

	Ammonia concentration (mg/L)			
	Tower 1		Tower 2	
Day*	Influent	Effluent	Influent	Effluent
22	13.5	11.7	17.3	16.5
24	13.5	10.2	15.2	10.8
25	12.8	9.6	14.0	9.2
35	11.5	7.5	12.5	6.5
39	5.8	4.4	4.8	2.0
42	6.1	3.6	6.7	2.6
43	6.0	2.8	7.0	2.2
44	4.9	3.1	6.5	2.5
45	6.1	4.0	6.1	2.2
46	6.7	4.0	7.2	1.7
51	14.0	11.4	13.0	5.5
52	17.2	14.4	15.6	7.0
58	20.3	18.3	19.6	14.8
66	22.8	21.0	23.5	18.5
74	14.2	12.5	14.2	9.9
134	22.3	21.3	—	—
135	16.5	16.0	—	—
136	20.2	19.5	20.8	19.5
137	19.1	18.0	20.0	18.7
141	15.5	14.5	12.7	11.9
147	26.2	25.5	24.1	24.0
148	25.3	25.2	25.0	23.2
149	28.5	27.2	—	—
155	28.1	26.3	27.3	25.8
156	30.9	30.1	31.0	28.7
157	28.1	27.0	28.5	26.9
158	24.5	23.4	26.0	21.3
198	27.0	25.0	31.0	22.0
199	23.0	22.0	21.0	21.0
200	25.0	24.0	24.0	23.0
204	25.0	23.0	24.0	23.0
205	23.0	21.0	24.0	23.0
206	22.0	21.0	24.0	23.0
207	22.0	22.0	24.0	23.0
210	24.1	23.8	25.2	25.0
213	21.9	21.0	22.2	22.2
214	21.3	21.3	22.1	22.0
219	26.2	25.1	—	—
228	24.8	23.5	—	—
240	22.7	21.9	—	—
242	20.9	20.2	—	—
243	23.0	22.9	—	—
248	18.2	17.1	—	—

*Note: Day 22 is 17 July 1984, Day 248 is February 26 1985, etc.

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